Combustion Research Facility

Light-Duty Diesel Combustion

Light-Duty Combustion Experiments

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Light-Duty Combustion Modeling

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Program Manager: Gurpreet Singh, DOE EERE-OVT

Project ID # ACE002

Overview

Budget:

DOE funded on a year-by-year basis

- SNL \$740k (FY13), \$750k (FY12)
- UW \$200k (FY13), \$230k (FY12)

Partners:

- 20 industry/national laboratory partners in the Advanced Engine Combustion MOU
- Close collaboration with GM and Ford diesel groups
- Additional post-doc funded by GM

Timeline:

- Project has supported DOE/industry advanced engine development projects since 1997
- Direction and continuation evaluated yearly

Barriers addressed:

A	Lack of fundamental knowledge
B, G	Lack of cost-effective emission control
C	Lack of modeling capability

Technical targets addressed:

- 40% diesel fuel economy improvement
- Tier 2, bin 2 emissions
- Emission control efficiency penalty < 1%
- 30 \$/kW power specific cost

(Barriers/Targets from EERE-VT 2011-15 Multi-year plan)

Technical/Programmatic Approach

Objective:
- **Develop a fundamental understanding of the combustion process**
- **Validate and improve computational tools for design**

SNL Optical Engine
- Optical measurements of flow and species
- Emissions and pressure analysis
- Model assessment

DOE & GM funded

GM 1.9 ℓ head/cylinder set

UW Simulations
- Interpretation of experiment
- Model development
- Optimization methodologies
- Numerical studies

DOE & GM funded

Programmatic Leverage:
- Closely coordinated program with both modeling and experiments
- Significant leverage of DOE funds by support from other sources
- Focused on an engine platform used by several other research groups (UW, ORNL)
- Collaboration with SNL heavy-duty research to generate unified understanding
- Input from and technical transfer to industry strongly established

Collaborations

Within Vehicle Technologies program:

- Formal collaboration between SNL-UW
- Data transfer to OEMs, NDA's (Ford/GM) to allow transfer of geometry
- Regular teleconferences (GM/Ford)
- Collaboration with heavy-duty/cross-cut projects (ACE001 and ACE005)
- Participation in Advanced Engine Combustion group, including presentations and discussion with 21 industrial/national laboratory partners:

Ex-Vehicle Technologies program:

- Separate GM funding
- Strong ties with Lund University, Friedrich-Alexander University, Université de Poitiers
  - Exchange students perform research at Sandia
  - Joint review articles on engine flows and combustion
  - SNL staff participates in LU research projects

Overview of Technical Accomplishments

- Measurement, simulation, and analysis of in-cylinder equivalence ratio distributions:

  Status March 2012: Quantitative toluene/*n*-heptane/*iso*-octane planar laser-induced fluorescence (PLIF) technique developed and applied to baseline 3 bar IMEP operating condition. R_s and P_{inj} sweeps performed

  Progress past 12 months:

  - Quantitative analysis of baseline operating condition, R_s and P_{inj} sweeps. Correlation of ϕ distributions with measured UHC & CO distributions. Comparison with simulations, impact on heat transfer losses
  - Measurement and analysis of SOI effects for both early-injection (PPCI) and late-injection (MK) LTC strategies. Identification of dominant role of kinetics
  - Vertical plane imaging performed to capture bowl/squish volume fuel split
  - Development and first application of 1-methylnaphthalene/*n*-cetane/*iso*-cetane PLIF technique to better match real fuel volatility.

- Scoping studies of pilot, split, and post injection strategies on UHC, CO, soot, and noise under light-load LTC conditions

Relevance

- The mixture formation process directly impacts soot, NO_X, HC and CO emissions as well as combustion noise. *Trade-offs adopted seeking to balance these factors unequivocally impact BSFC, e.g.*:
  - Excessive near-stoichiometric mixture near ignition leads to high noise and high NO_X, thereby forcing non-optimal combustion phasing (timing retard)
  - Noise reduction in early-injection LTC strategies requires higher EGR than is needed for NO_X control, leading to combustion inefficiency and slow burning
- *In-cylinder* emission control is critical under cold-start conditions
- Multiple injection strategies impact the details of the mixture formation process and the time available for mixing and *can improve both emissions and BSFC*

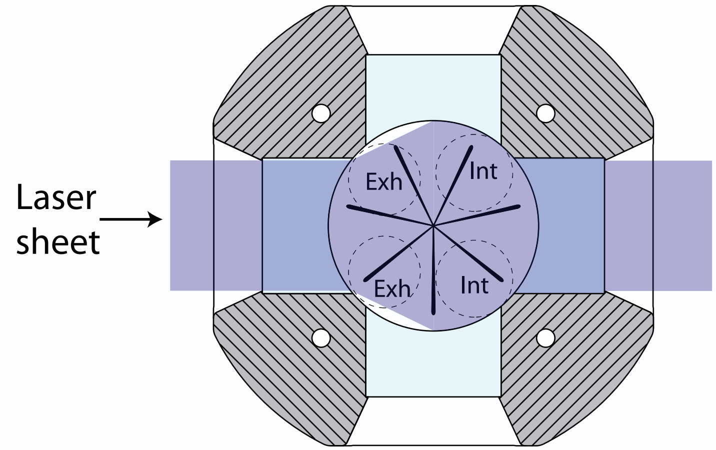
A better understanding of the mixture formation process and better predictive tools directly addresses EERE-VT technical targets:

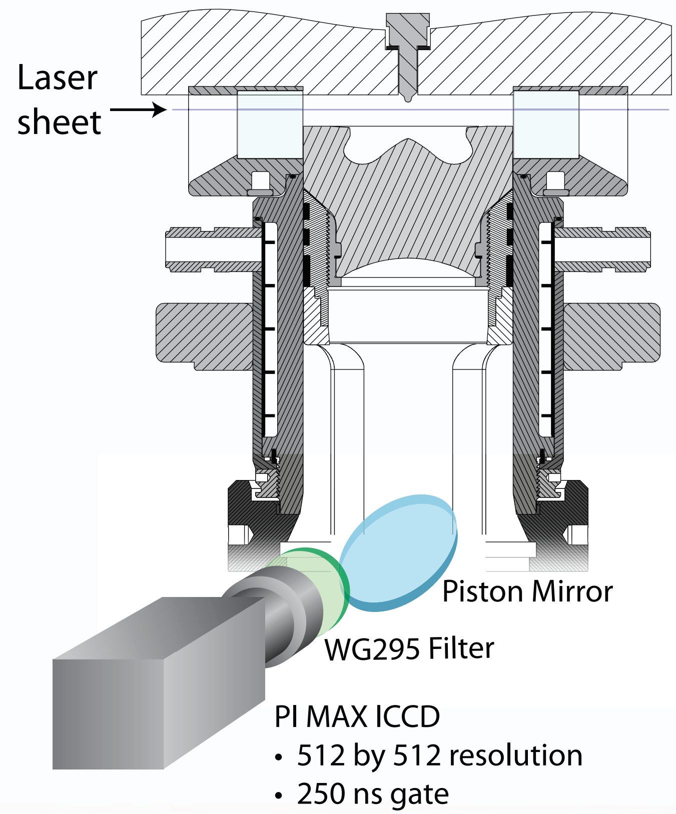
- 40% diesel fuel economy improvement
- Tier 2, Bin 2 emissions
- Emission control efficiency penalty < 1%
- 30 $/kW power specific cost

Engine Facility and Experimental Set-up

Measurements are made in a GM 1.9L optically accessible engine

- Piston geometry has production-like bowl and valve pockets
- Top ring-land crevice approximately 3–4 times volume of production engine crevice
- Gap-less compression rings reduce blowby
- Recessed liner windows allow squish volume access @TDC
- Fluorescence collected through piston





Engine Geometry

Bore	82.0 mm
Stroke	90.4 mm
Displ. Volume	0.477 L
Geometric CR	16.7
Squish Height	0.88 mm

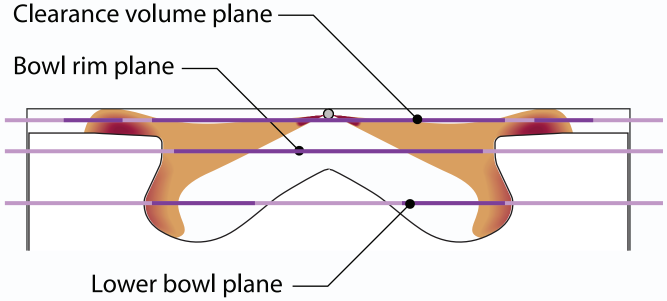
Injector specifications

Injector	Bosch CRI2.2
Nozzle Type	Mini Sac (0.23 mm^3)
Holes	7
Nozzle diameter	0.139 mm
Included Angle	149°
Hole geometry	KS1.5/86

Measurement Overview

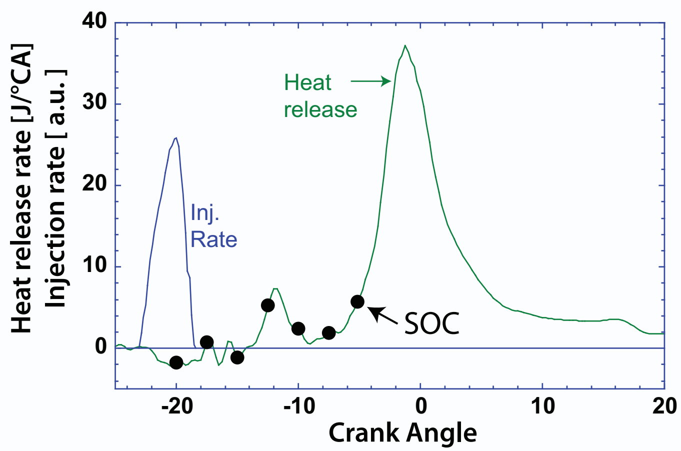
SOI = -23.3°, R_S = 2.2, P_{inj} = 860 bar

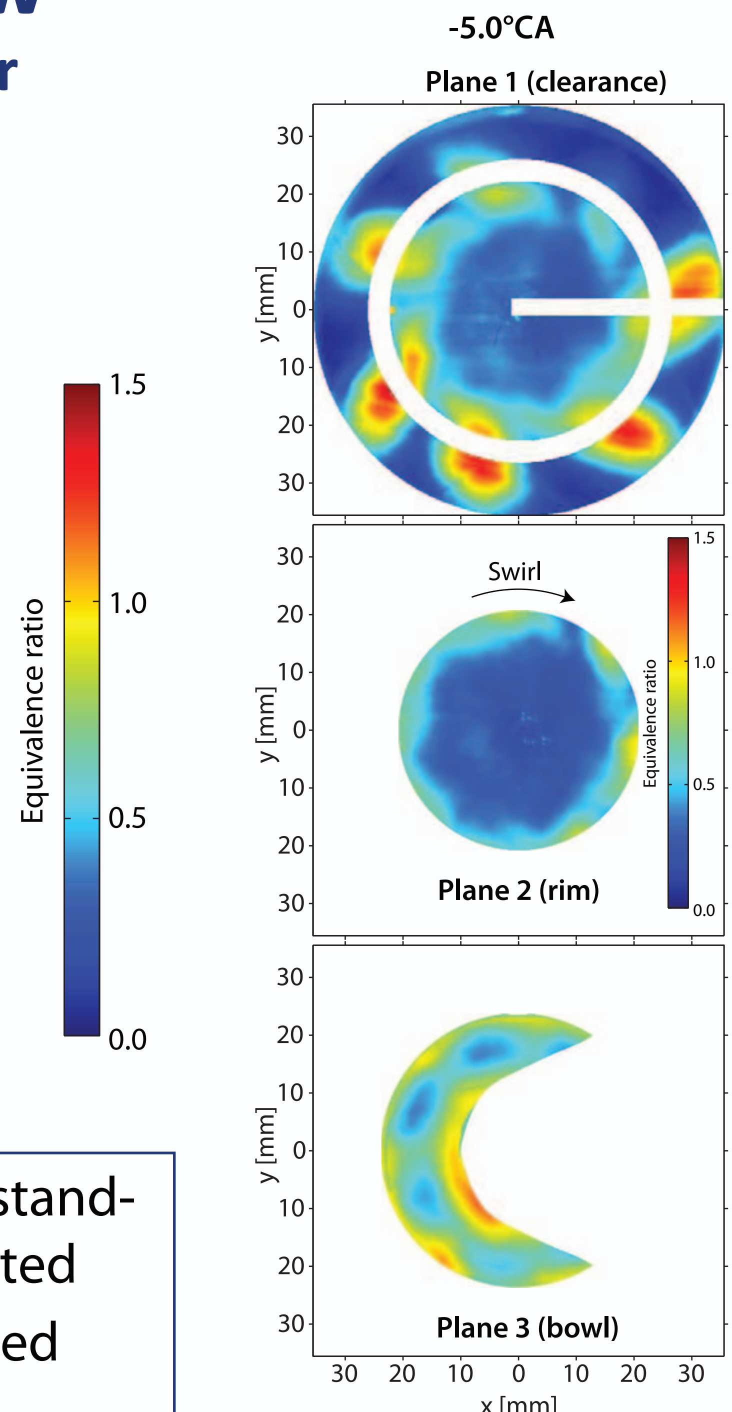
Measurements are made in three planes...



Darkened areas of the laser sheet indicate visible regions

...through the start of HTHR (SOC)





- The distributions at SOC allow a significant understand-ing of the origins of HC/CO emissions to be extracted
- The mixture preparation process is clearly illustrated and provides unique data for model validation

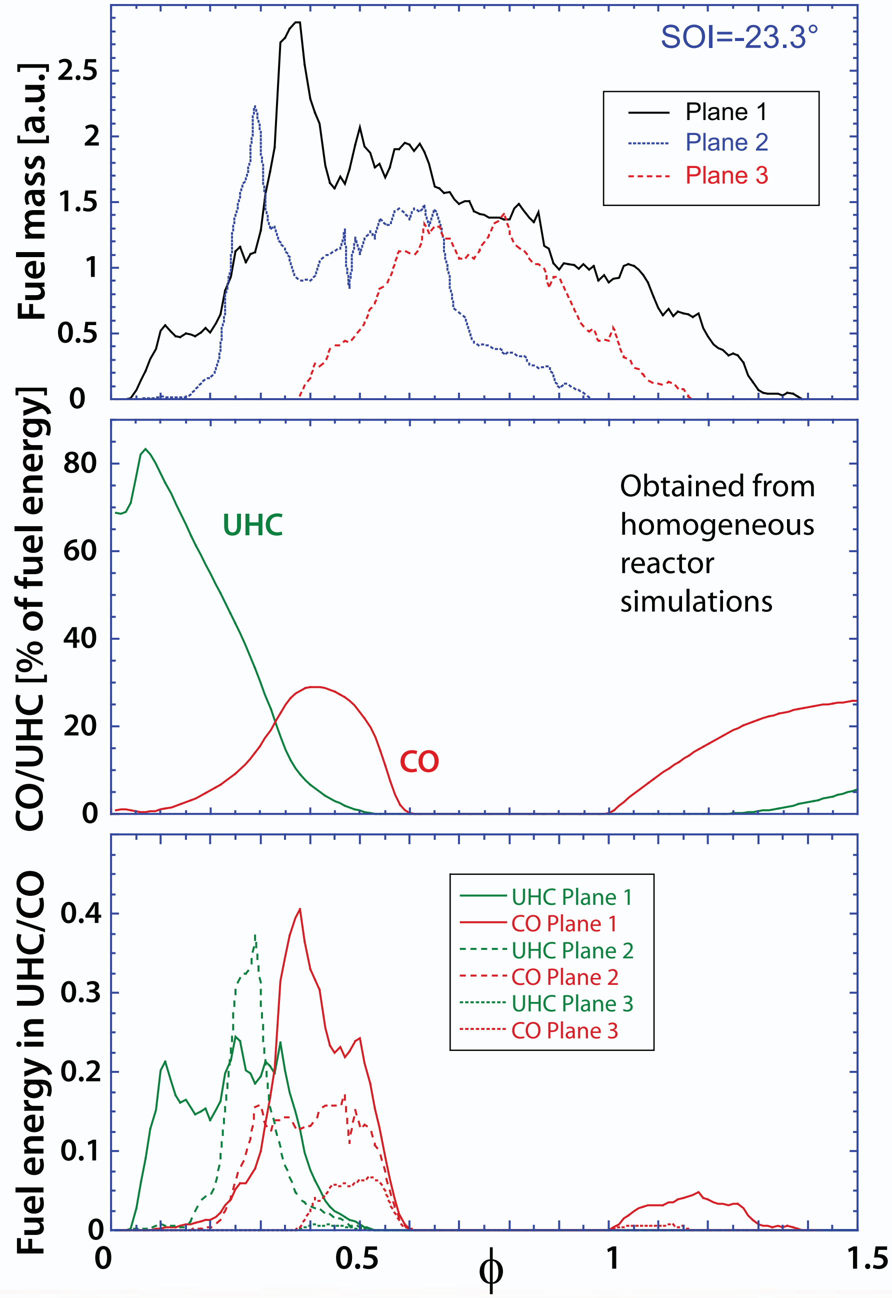
Homogeneous reactor simulations link ϕ distributions at CA10 to emissions

- The fuel mass at each ϕ can be computed from the images

$$m_{fuel}(\phi) = \sum_{j}^{N_j}\sum_{i}^{N_i} m_{fuel,i,j}(\phi) = \sum_{j}^{N_j}\sum_{i}^{N_i} \phi_{i,j} m_{\text{charge},i,j} \left(\frac{m_{fuel}}{m_{\text{charge}}}\right)_{stoich}$$

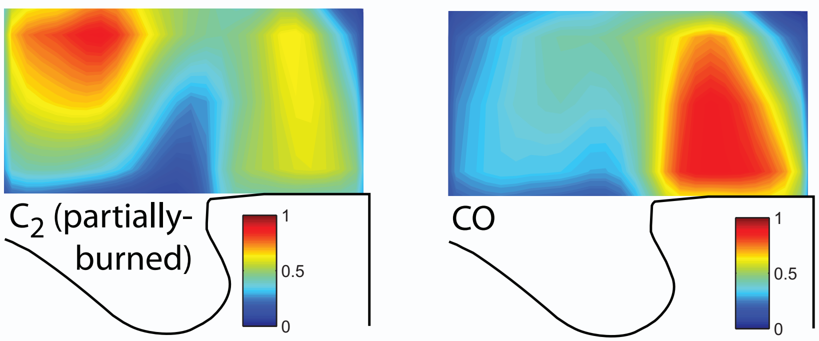
- Multiplied by the UHC or CO yield predicted in the absence of further mixing

- To provide a qualitative prediction of UHC and CO emissions from both rich and lean sources

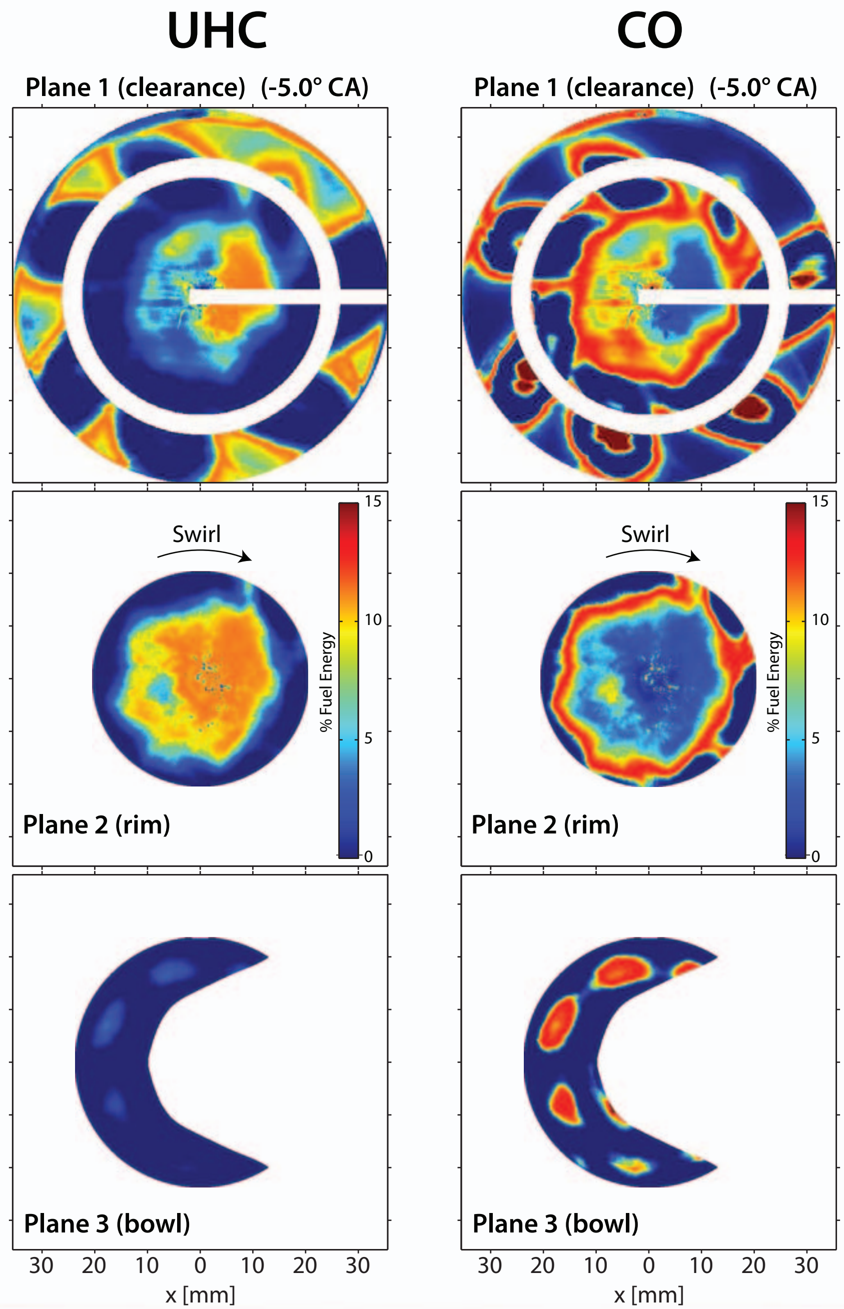


We can also generate images of expected UHC & CO distributions

- Strong bias toward UHC & CO sources from lean mixture in the upper cylinder & squish volume
- In-cylinder UHC/CO dominated by these same regions:



- **Strong evidence that CO and UHC emissions are very closely linked to the initial mixture preparation process**



Impact of Injection Pressure on HC/CO yield
(ϕ dist. @ CA10)

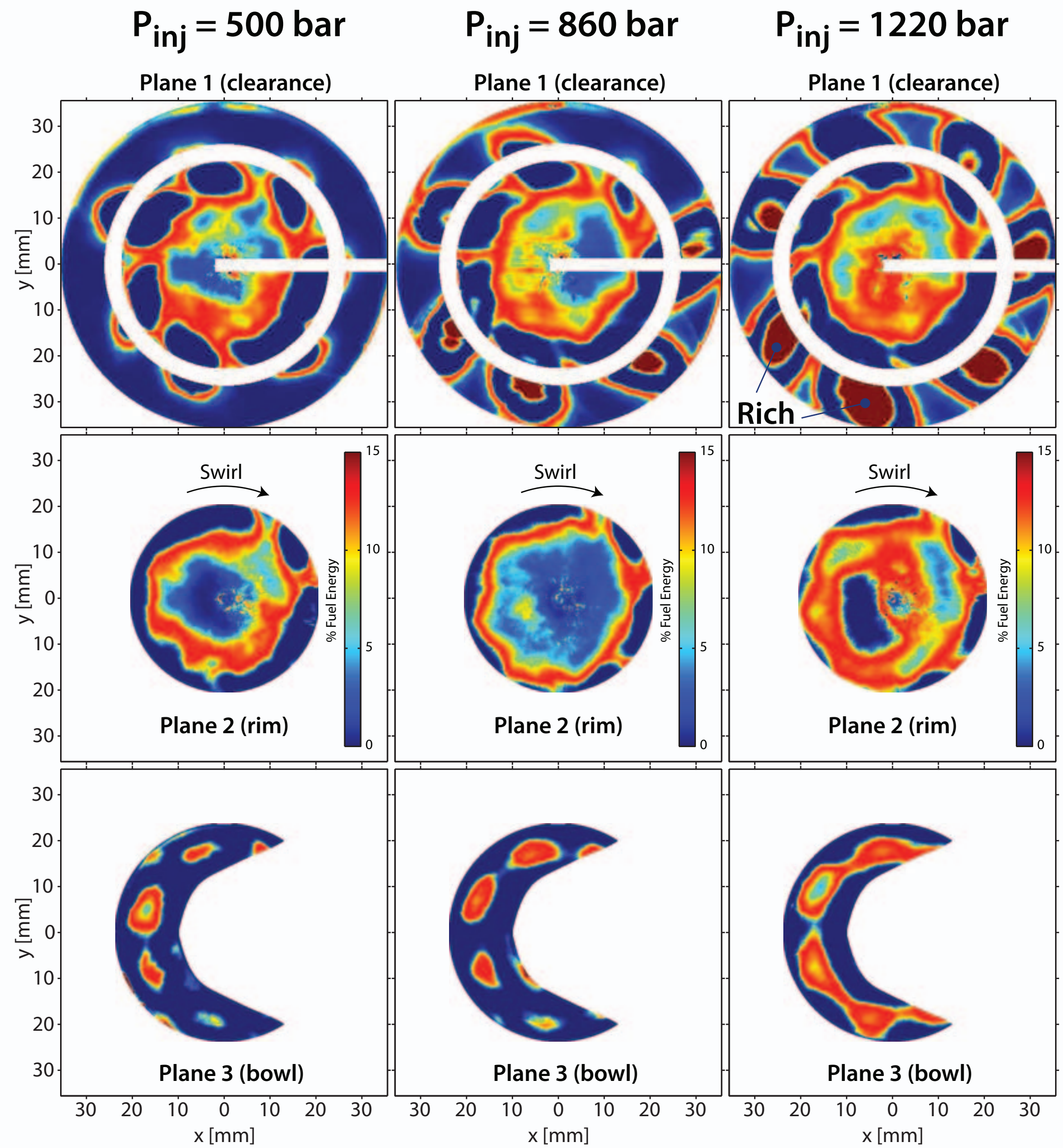
Increased P_{inj} gives:

- Greater jet penetration into the squish volume, with more jet peripheral area (crevice UHC)
- Higher ϕ in the head of the jet, with greater potential for rich-mixture CO (and soot & UHC)
- More over lean mixture in the upper-central region of the combustion chamber
- More over lean mixture deep in the bowl

Engine emissions:

P_{inj} [bar]	CO [g/kg-f]	UHC [g/kg-f]
500	**96.7**	10.5
860	**121.2**	11.2
1220	**130.0**	11.0

Expected CO Yield



Impact of Swirl Ratio on HC/CO yield

Start of HTHR (CA10)

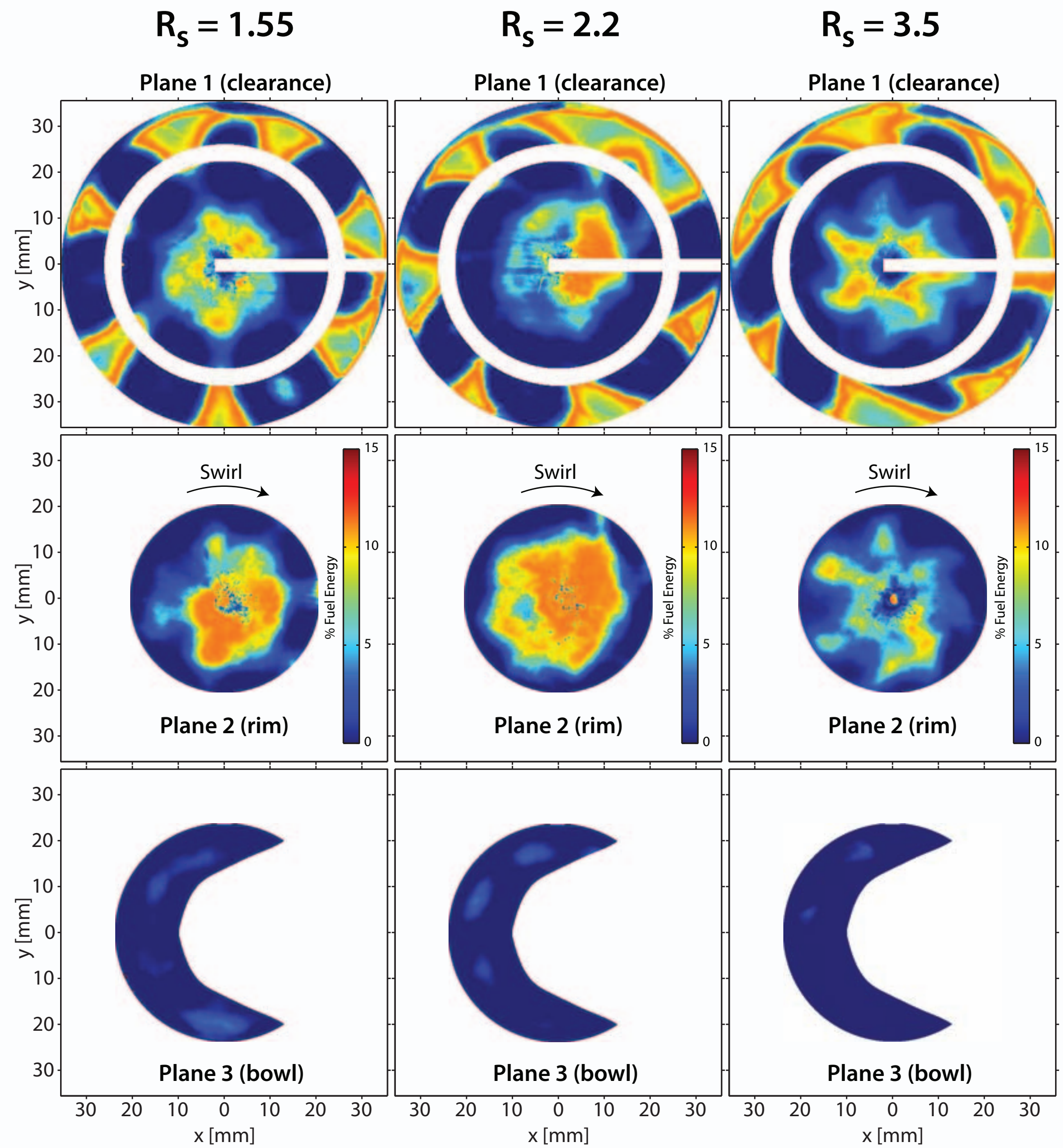
Emission behavior is explained by a trade-off between the emissions from different regions

- UHC and CO sources initially increase with swirl due to increased lean mixture in both the upper cylinder and the squish volume
- Lean squish volume sources increase at all swirl ratios
- With higher swirl HC/CO from the bowl drop due to mixture stratification

Engine emissions:

R_s	CO [g/kg-f]	UHC [g/kg-f]
1.55	96.2	8.9
2.2	117.8	10.5
3.5	95.3	12.3
4.5	87.6	11.6

Expected HC Yield

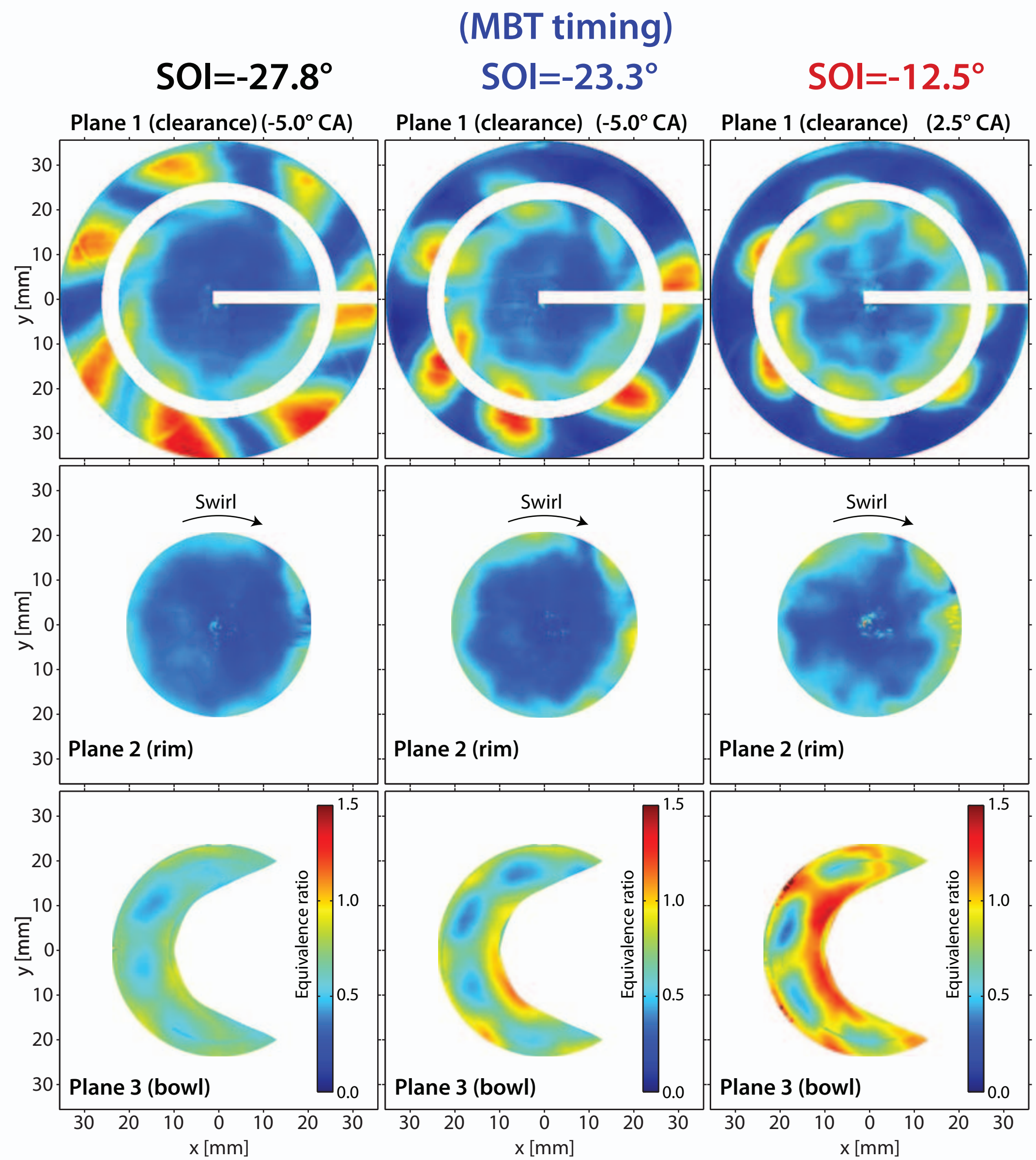


Impact of Injection Timing

Clear trends observed as injection is retarded:

- Less fuel in the squish volume, less penetration, lower peak ϕ
- Less lean mixture between the heads of the jets
- Less over-lean mixture in the upper-central regions
- Richer mixtures deep in the bowl, but not overly rich

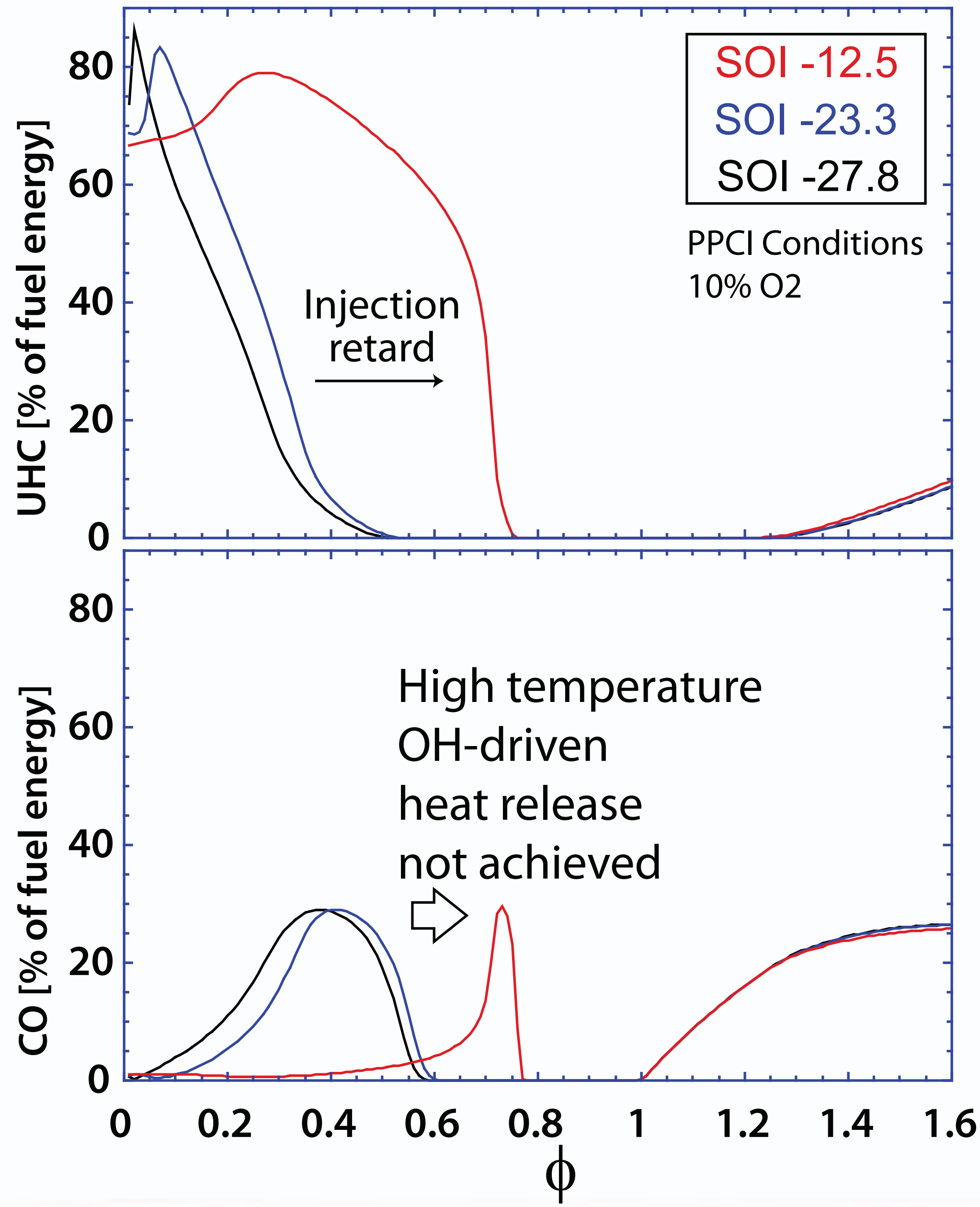
From a mixture preparation viewpoint, retarded injection is preferred



Retarded injection significantly impedes lean mixture oxidation

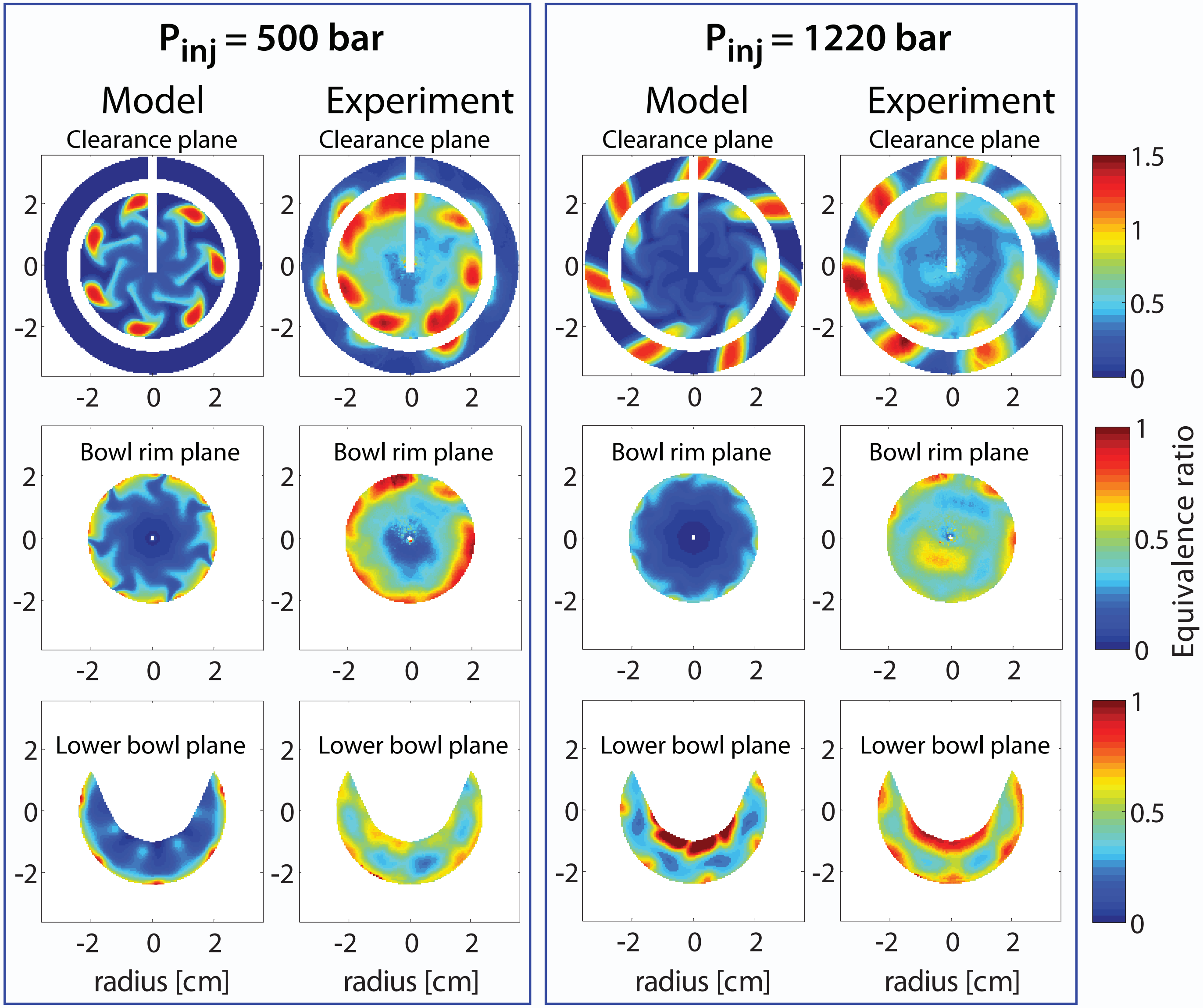
- Retarded SOI significantly increases the ϕ at which complete oxidation occurs
- UHC emissions suffer to a greater extent than CO (slow reaction impedes formation of CO)

Optimal SOI timing is due to a balance between mixture formation and kinetics of oxidation



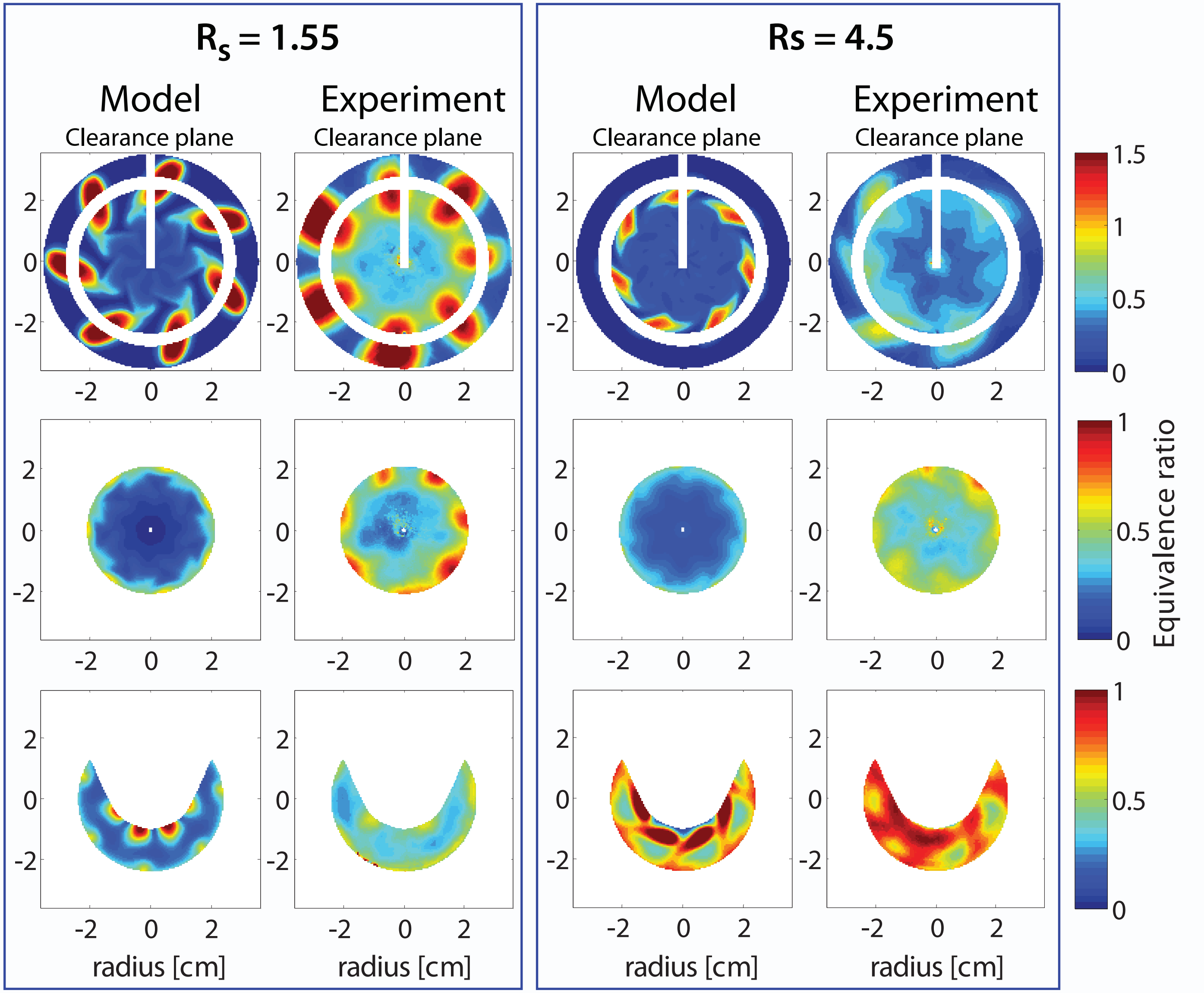
Comparison with model: Impact of P_{inj}

- Peak ϕ well predicted
- Penetration under predicted at low P_{inj} in both the squish volume and the lower bowl
  - models calibrated at higher P_{inj}. We are re-calibrating against low P_{inj} ECN data
- Turbulent diffusion clearly under-predicted
  - seemingly inconsistent with under predicted penetration
- Over-lean mixture in upper cylinder poorly predicted



Comparison with model: Impact of swirl

- Penetration into the squish volume under predicted at high R_S; lower bowl penetration seems reasonable
- Jet deflection over predicted at all R_S
- Turbulent diffusion again under-predicted
- Over-lean mixture in upper cylinder poorly predicted



Discrepancies in model predictions suggest two main courses of action

- Turbulent diffusion is under-predicted
- Jet deflection, penetration, and turbulent diffusion are overly sensitive to swirl (this observation encompasses low injection pressure result)
  - Over-prediction of jet entrainment would result in greater jet deflection, lower penetration, but ***not an under prediction of spreading/diffusion***
  - Over-prediction of the swirl velocity is a more consistent possibility (greater deflection, lower penetration, 2nd-order impact on diffusion) ✓
  - Inaccurate swirl prediction in the squish volume more likely ✓ (valve pockets, head features absent due to use of sector mesh)

Action: Examine mean flow differences observed with a detailed, 360° mesh

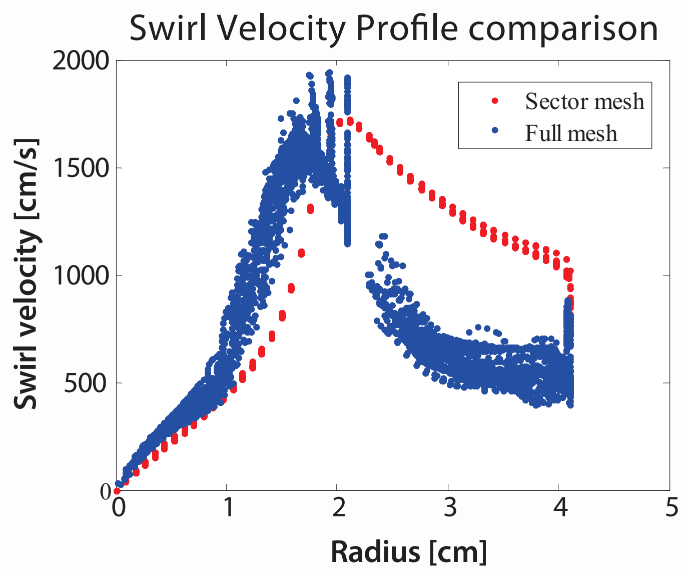
- Over-lean mixture in upper cylinder poorly predicted
  Critical for accurate prediction of low-load UHC/CO

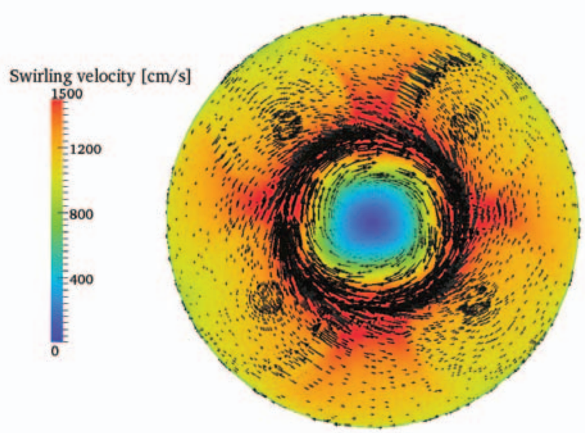
Action: Examine gas jet model performance in predicting end-of-injection increase in entrainment (model based on steady jet theory)

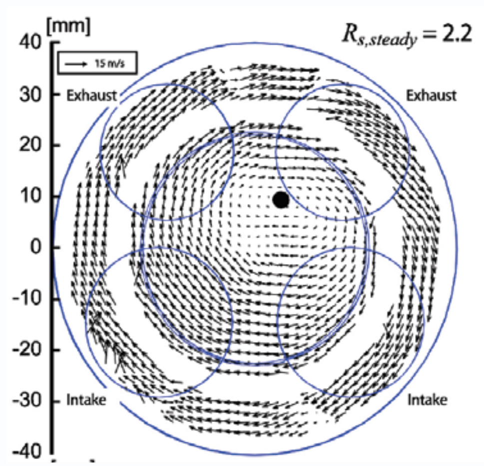
A 360° mesh results in significant differences in the swirl flow in the upper cylinder

Early results:

- Large differences in the swirl velocity are seen, especially within the squish volume





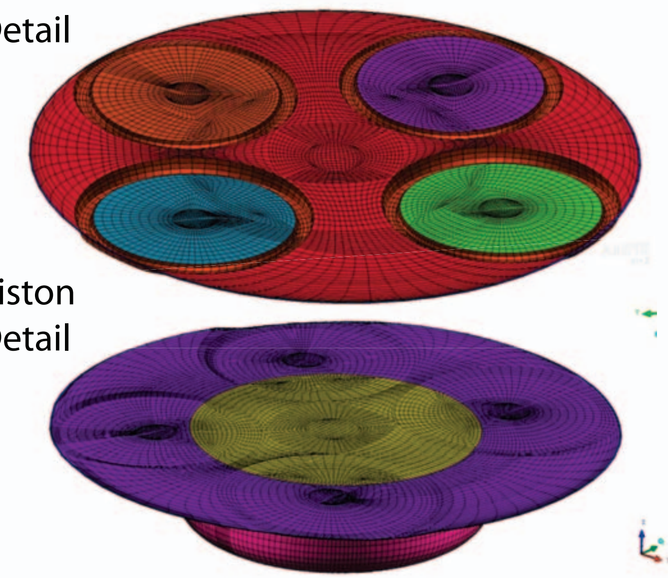


- Absent computation of the induction stroke, flow asymmetries (offset swirl) will not be captured

360° mesh

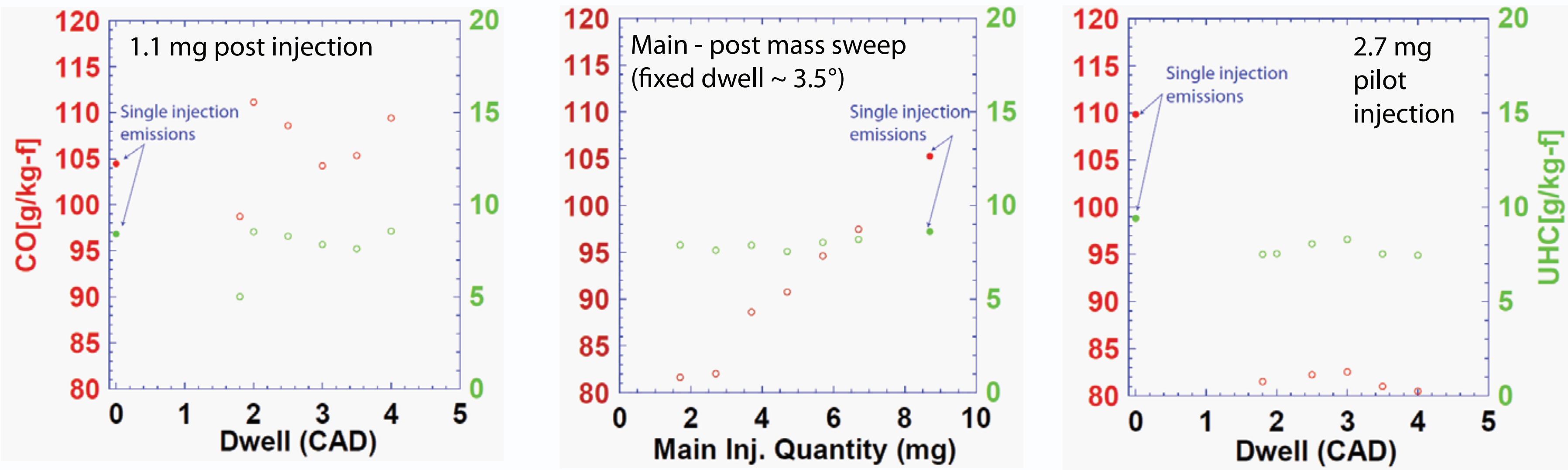
Head Detail

Piston Detail



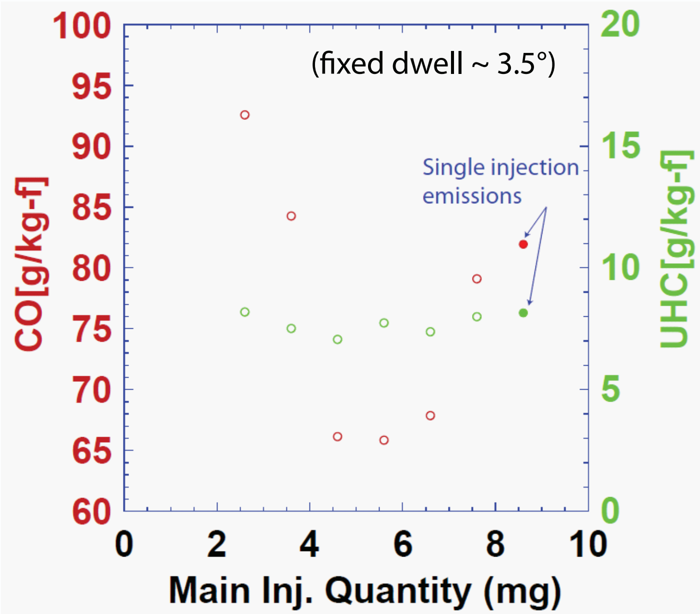
Simulations of the fuel injection event with the 360° mesh are in progress

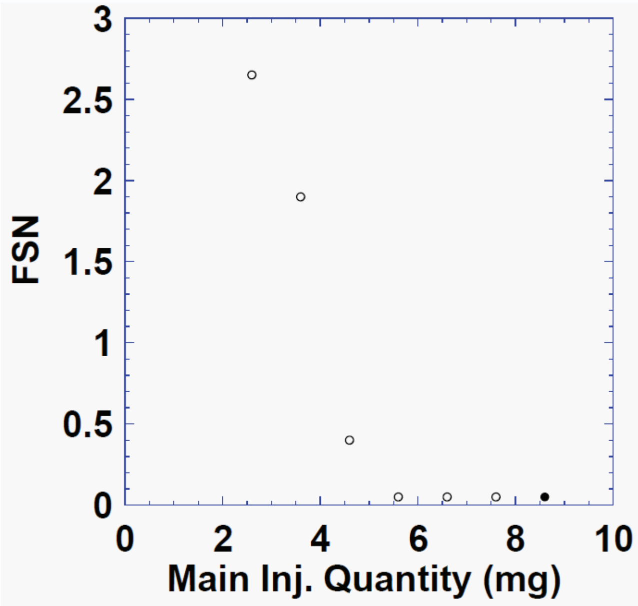
Pilot injection strategies offer the best potential for mitigating light-load HC/CO at higher injection pressure (860 bar)



- Close-coupled post injections offered only a small benefit (6-7% reduction)
  - Unlikely to impact HC/CO emissions stemming from the squish volume
- Best CO reduction potential is provided by a pilot-like injection strategy
  - Minimizing ignition delay most promising strategy to reduce squish volume emissions
  - Impact of pilot injection fairly insensitive to dwell
  - Soot is always low at this injection pressure

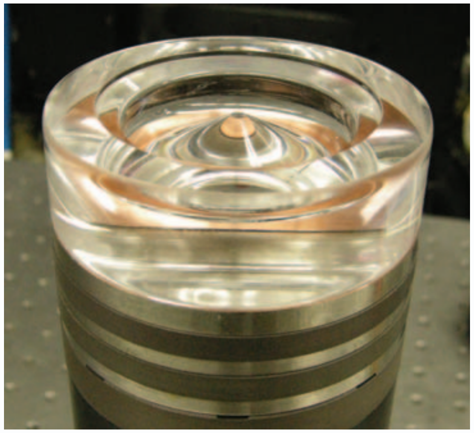
With a lower injection pressure (500 bar) split injection strategies are most effective





- A 60-40 split offers a 20% reduction in CO emissions
  - CO emissions are dominated by over-lean mixture in the upper-central cylinder at this injection pressure
  - Soot emissions can become problematic if the first injection quantity is too small
  - Combustion noise can increase slightly

Future work



- Investigation of piston geometry effects on mixture formation and multiple injection strategies to mitigate emissions
  - Pistons with a stepped-lip bowl geometry specified by Ford have been procured and will be benchmarked against our conventional bowl
  - Extend mixture formation measurements to higher loads (8 bar IMEP has been successfully investigated in our optical engine)
- Further assessment of multiple injection strategies
  - Light-load strategies for mitigation of HC/CO emissions. Explore synergies between LTC and pilot injection strategies; examine pilot ignition process under low-temperature, dilute conditions and its subsequent interaction with main injection ignition
  - Investigate idle or very light-load mixture stratification potential by coupling swirl to multiple small injection events
  - Explore higher load strategies focusing on smoke and noise reduction
- Examine and improve near nozzle submodels and identify best modeling practice needed to accurately predict flow and mixture formation processes
- Extend multi-component vaporization model to include diesel PRFs

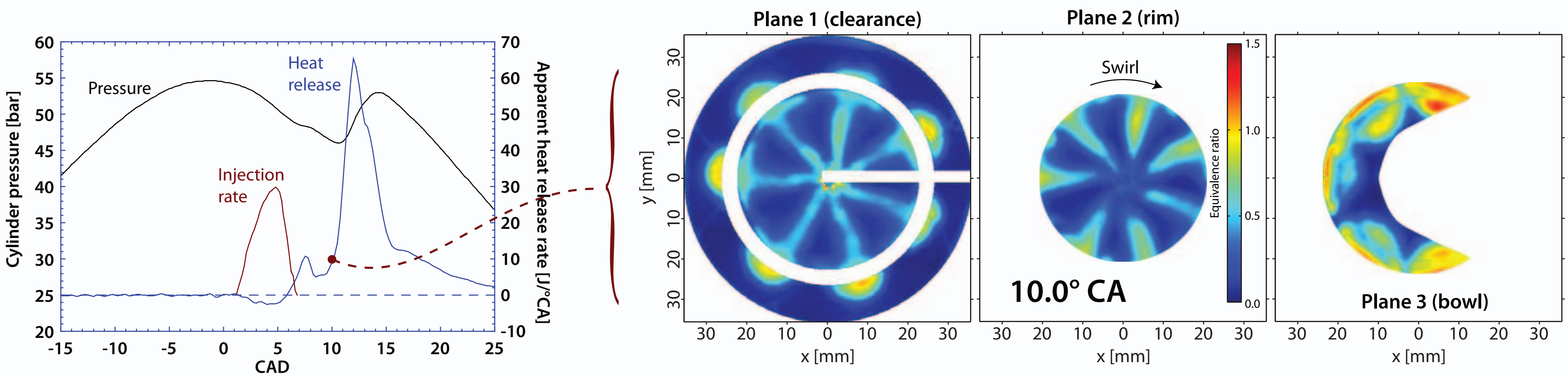
Light-Duty Diesel Combustion Summary

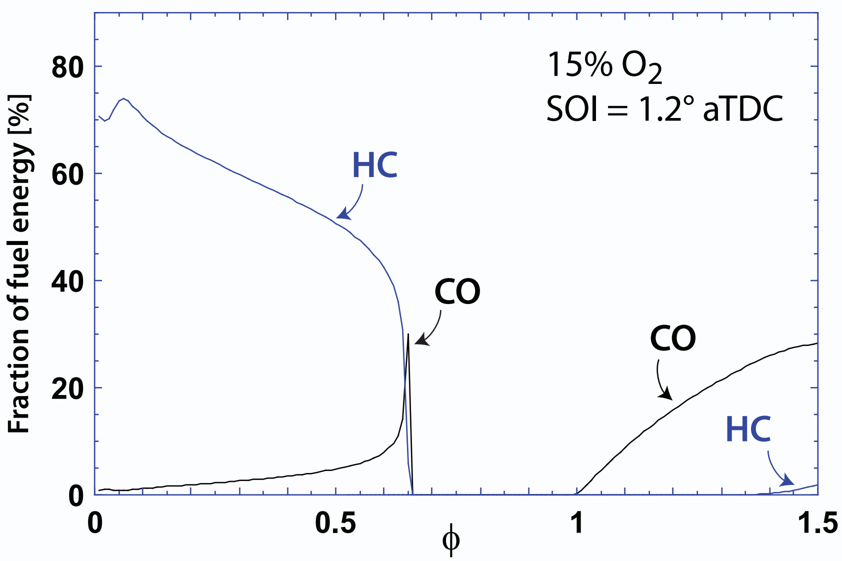
- The initial mixture formation process critically impacts HC/CO emissions
- Variations in P_{inj} and R_s change the relative importance of sources of HC/CO (*e.g.* squish volume, central bowl)
- The optimal multiple injection strategy for reducing HC/CO emissions varies as the sources of HC/CO vary
- MBT timing of light-load PPCI combustion is determined principally by a trade-off between mixture formation and oxidation kinetics
- Poor emissions from MK-like combustion systems with excessive timing retard are associated primarily with oxidation kinetics, not extended mixing times
- Discrepancies between model predictions and experiments point to:
    - Need for geometrically accurate, 360° mesh
    - Full induction stroke calculation to capture asymmetries
    - Further examination of near-nozzle entrainment models
- Simulations have identified significant impact of P_{inj} & R_s on heat transfer & η
- Both experimental and simulation efforts are well situated to make further progress with new pistons, new injection equipment, and detailed 360° mesh

Technical Backup Slides

Technical backup: MK combustion is also largely limited by kinetics, not over-mixing

- Mixture preparation at SOC is very good - neither overly lean nor overly rich

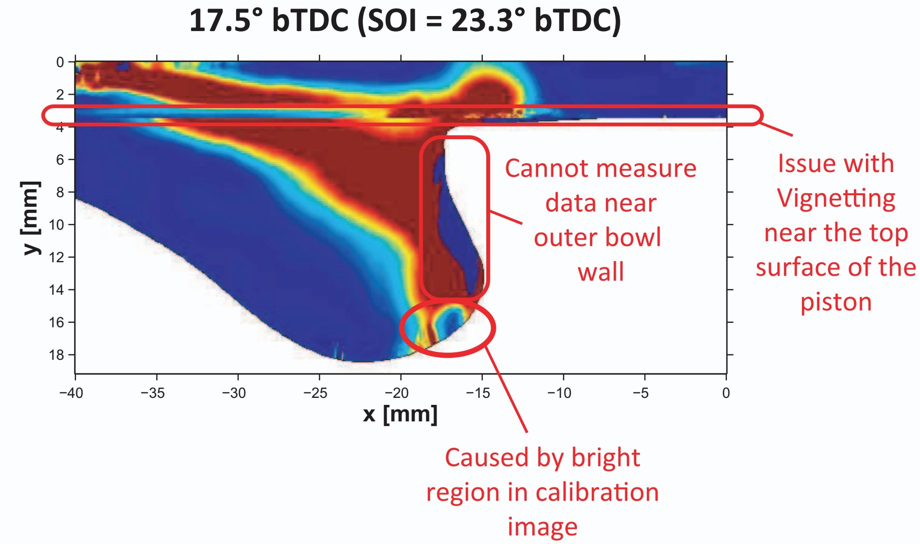


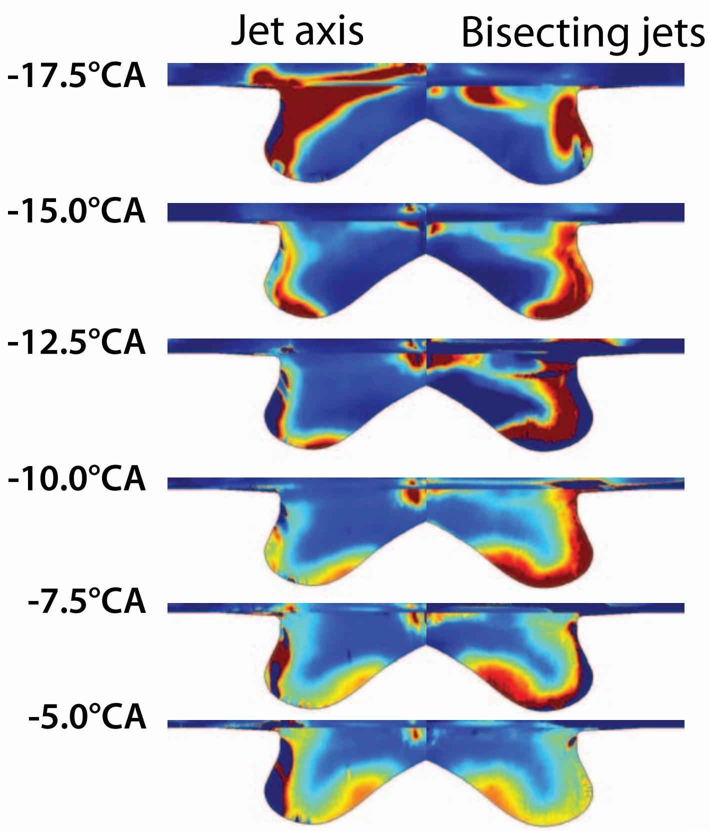


- Slow oxidation kinetics require $\phi > 0.65$ to ensure complete oxidation
- The cause of the rapid increase in HC relative to CO as injection is retarded is due to the oxidation kinetics

Technical back-up: vertical plane imaging provides qualitative fuel distributions

- Quantitative vertical plane imaging proved difficult due to internal bowl reflections, vignetting, and low signal levels



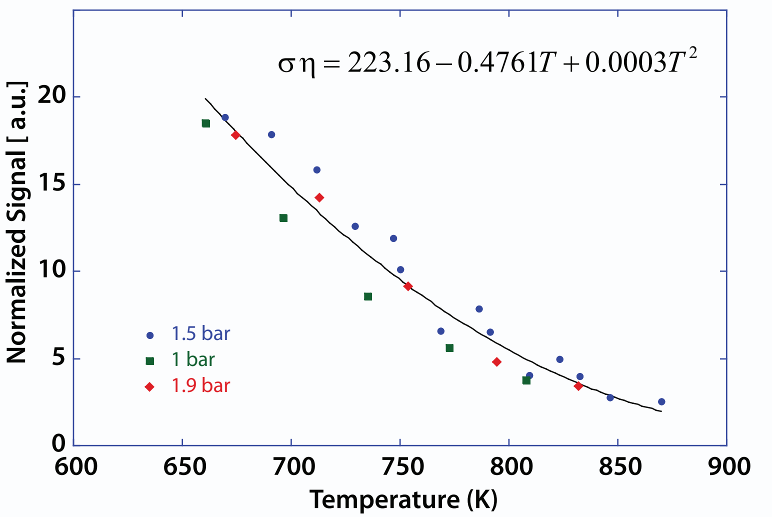


- Nevertheless, a good qualitative indication of fuel distributions within the bowl is provided
- At the time of ignition (-5°), a surprising degree of symmetry has been achieved

Technical back-up: a new LIF diagnostic based on 1-methylnaphthalene and the diesel PRFs has been developed

- A much better match to the density, viscosity, and volatility of diesel fuel is achieved

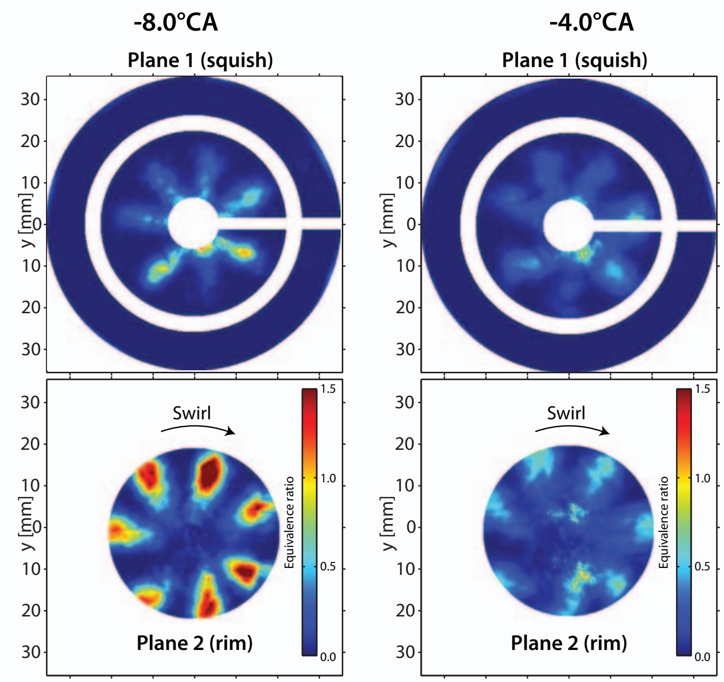
		D#2	HD	HMN	1MN	Heptane	Octane	Toluene
			Toluene/ Gasoline PRF System			Toluene/ Gasoline PRF System		
Molar Mass	g/mol	-	226.4	226.4	142.2	100.2	114.2	92.1
Density (at 25°C)	kg/l	0.820 - 0.845	0.773	0.793	1.001	0.664	0.694	0.857
Viscosity (at 40°C)	mm^2/s	1.9 - 4.1	3.01	3.20	5.34	0.505	2.67	0.545
Boiling Temp.	°C	176 - 370	287	240	240-243	99	99	110-111



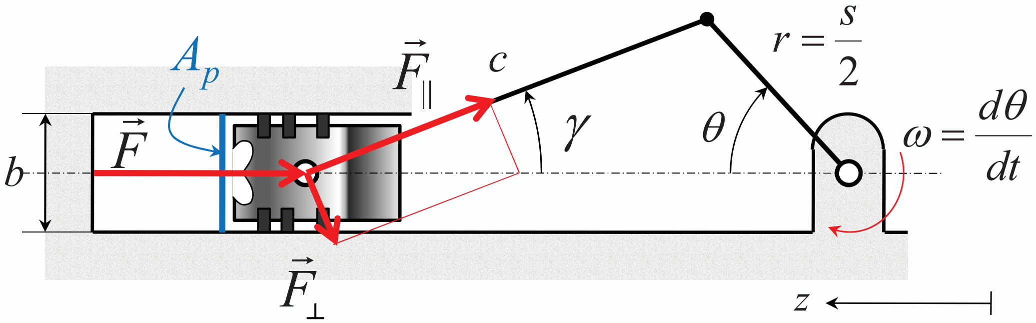
- The fluorescence yield is temperature dependent, but has little dependency on pressure

1 mg pilot

- Pilot injection mixing studies show improved signal levels over toluene based LIF technique



Technical back-up: a deformable connecting rod model has been implemented to account for optical engine piston compliance

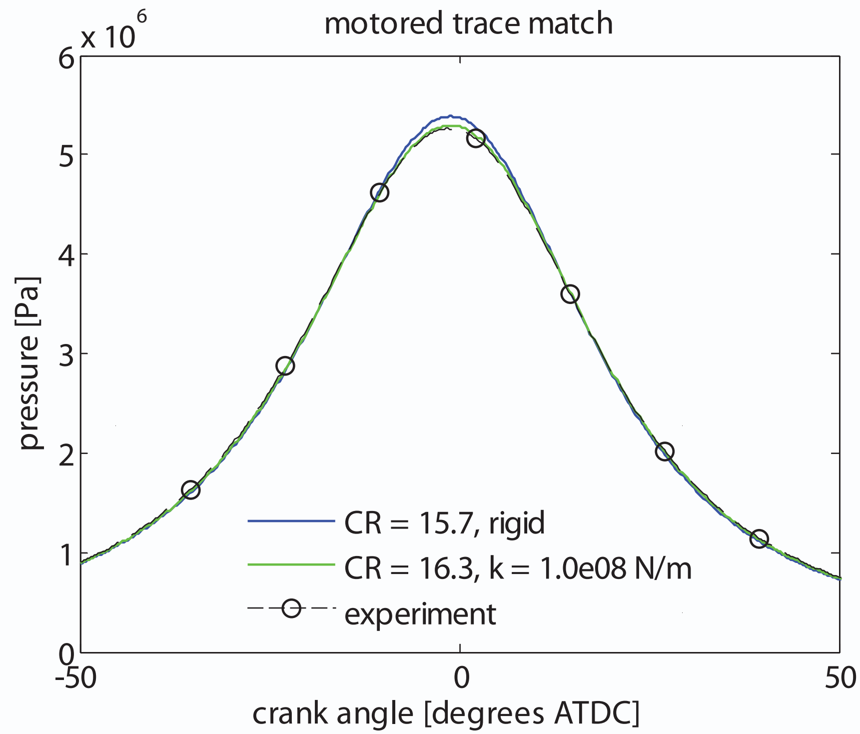


$$F_{\parallel} = -k\,\Delta c$$

$$F_{\parallel} = A_p\, p_{cyl} \sqrt{1 - \lambda^2 \sin^2 \theta}$$

$$\frac{dz_P}{dt} = -\frac{s}{2}\omega \sin\theta \left(1 + \frac{\tan\gamma}{\tan\theta}\right) + \underbrace{\frac{dc}{dt}}\cos\gamma$$

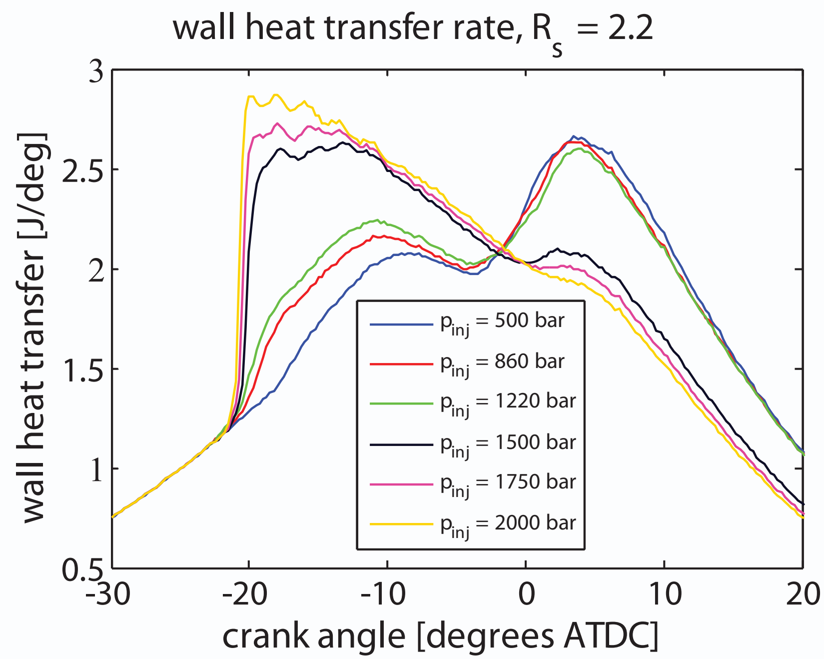
Impact of variable connecting rod length

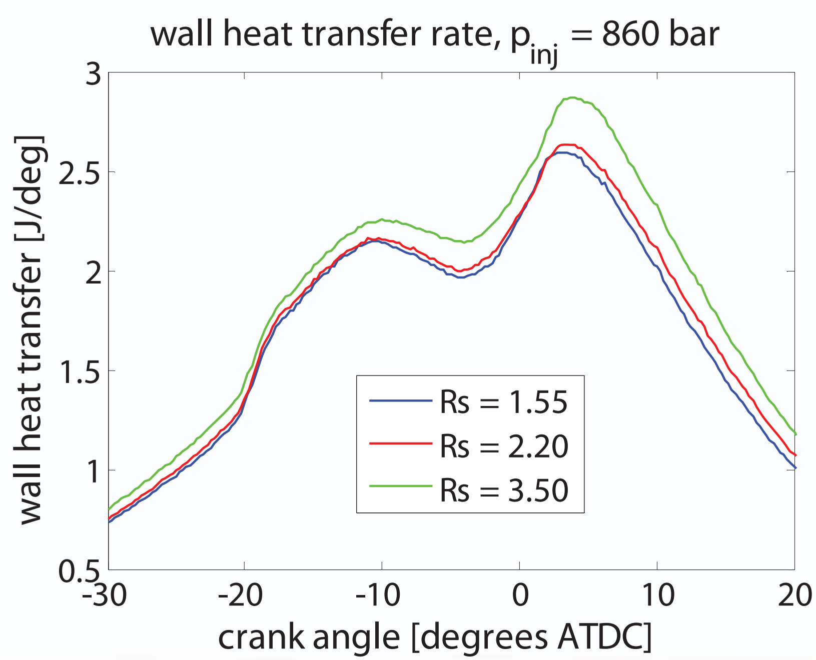


- Model closely accounts for peak pressure loss and deviations in the shape of the pressure trace observed with a rigid model

Technical back-up: simulations have explored the impact of P_{inj} and R_s on heat transfer loss

- Increased injection pressure impedes combustion efficiency through increased HC/CO and increased heat transfer losses
- Peak transfer rates are significantly advanced and can exceed to post-combustion peak heat transfer rate





- Increasing swirl from 1.55 to 3.5 increases heat losses by ~14 J, or 3.5% of the injected fuel heating value